INTRODUCTION

1.1 HISTORICAL USE OF FOUNDATIONS

Builders have realized the need for stable foundations since structures began rising above the ground. Builders in the time of the Greeks and the Romans certainly understood the need for an adequate foundation because many of their structures have remained unyielding for centuries. Portions of Roman aqueducts that carried water by gravity over large distances remain today. The Romans used stone blocks to create arched structures many meters in height that continue to stand without obvious settlement. The beautiful Pantheon, with a dome that rises 142 ft above the floor, remains steady as a tribute to builders in the time of Agrippa and Hadrian. The Colosseum in Rome, the massive buildings at Baalbek, and the Parthenon in Athens are ancient structures that would be unchanged today except for vandalism or possibly earthquakes.

Perhaps the most famous foundations of history are those of the Roman roads. The modern technique of drainage was employed. The courses below a surface course of closely fitted flat paving stones were a base of crushed stone, followed by flat slabs set in mortar, and finally rubble. The roads provided a secure means of surface transportation to far-flung provinces and accounted significantly for Roman domination for many centuries. Some portions of the Roman roads remain in use today.

1.2 KINDS OF FOUNDATIONS AND THEIR USES

1.2.1 Spread Footings and Mats

A diagram of a typical spread footing is shown in Figure 1.1. The footing is established some distance below the ground surface for several possible rea-
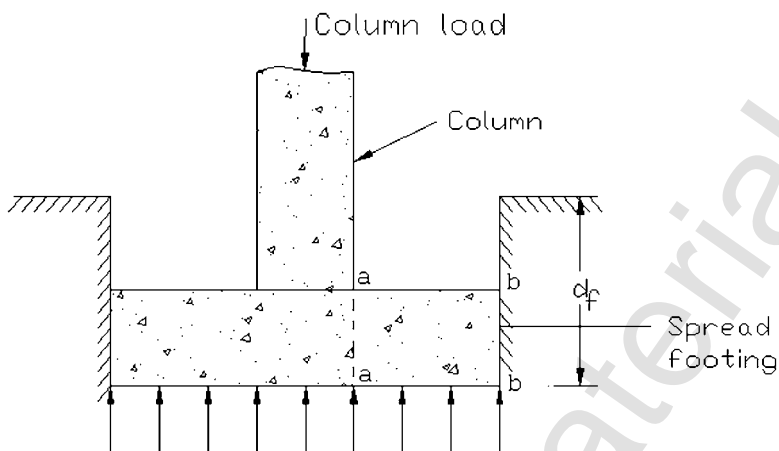
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Figure 1.1   Square or continuous footing with axial loading.

sons: to get below weak near-surface soil, to get below the frost line, to eliminate expansive clay, or to eliminate the danger of scour of soil below the footing. If the lateral dimension in Figure 1.1 is large, the foundation is termed a *mat*. Mats are used instead of footings if multiple loads are supported or if the foundation is large to support a tank. The distance d_f shown in the figure is frequently small, and footings and mats are called *shallow foundations*. The geotechnical design of shallow foundations is presented in Chapter 9.

The distribution of the soil resistance shown in Figure 1.1 is usually assumed, allowing the computation of the shear and bending moment at Section a-a for design of the reinforcing steel. If the concept of *soil–structure interaction* is employed, the downward movement of the footing at Section a-a would be slightly more that the downward movement at Section b-b. If the engineer is able to compute a new distribution of soil resistance for the deformed footing, a more appropriate value for soil resistance could be computed. However, the savings due to the lesser amount of reinforcing steel needed would be far less than the cost of engineering required for such analyses. For some soils, the soil resistance would be higher at Section b-b than at Section a-a even taking the deformation of the footing into account. Unless the dimensions of the footing are very large, the engineer could assume a distribution of soil resistance to give the largest bending moment at Section a-a without substantial cost for reinforcing. The concept of soil–structure interaction is discussed in the last five chapters of this book and illustrated by application to problems where the movement of the soil under load must be considered in detail in solving a practical problem.

Rather than being square, the footing in Figure 1.1 could be continuous to support the load for a wall or from a series of columns. With a series of

concentrated loads, the soil reaction would more complex than for a single column, but uniform distribution, as shown in Figure 1.1, is normally assumed.

Nominal stress distribution for the case of a square or continuous footing subjected to generalized loading is shown in Figure 1.2. Statics equations may be used to compute the distribution of vertical stresses at the base of the footing to resist the vertical load and moment. The stresses to resist the shear force may either be normal resistance at the edge of the footing or unit shear at the base of the footing. The engineer may decide to eliminate the normal resistance at the edge of the footing because of possible shrinkage or shallow penetration, allowing a straightforward computation of the shearing resistance at the base of the foundation.

A much larger shallow foundation such as a *mat,* and similar foundations are used widely. A *stress bulb* is a device sometimes used to illustrate the difference in behavior of foundations of different sizes. For equal unit loadings on a footing or mat, the stress bulb extends below the foundation to a distance about equal to the width of the foundation. Assuming the same kind of soil and a load less than the failure load, the short-term settlement of the mat would be much greater than the short-term settlement of the footing (settlement of footings and mats is discussed in Chapter 7). Thus, in the design of a mat foundation, the short-term settlement must be given appropriate consideration. Also, the structural design of the mat would plainly require more thought than that of the footing.

With regard to the design of mat foundations for residences on expansive clay, many designers use the BRAB slab recommended by the Building Research Advisory Board (1968). The mat includes a series of reinforced beams on the edges and interior of the mat, with dimensions depending on the nature
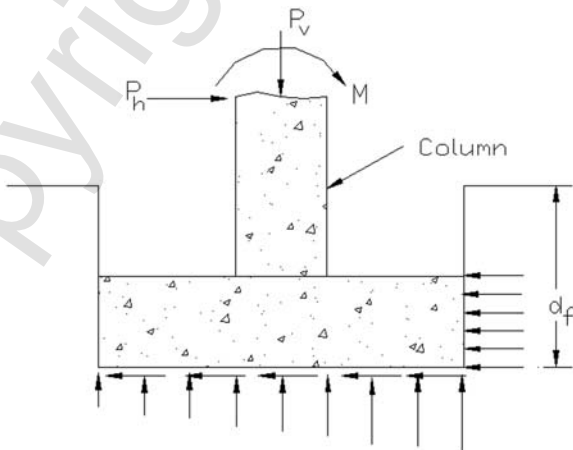

Figure 1.2 Square or continuous footing with generalized loading.

of the expansive clay. The concept is that the mat would have adequate bending stiffness to maintain a level surface even though, with time, differential movement of the clay occurs.

A view of a shallow foundation under construction is shown in Figure 1.3. The plastic sheets serve to keep the soil intact during the placement of concrete and prevent moisture from moving through the slab by capillarity. Communication cables may be placed in the slab. The deepened sections contain extra steel and serve as beams to strengthen the slab. The engineer has the responsibility to prepare specifications for construction and should be asked to inspect the construction.

1.2.2   Deep Foundations

Deep foundations are employed principally when weak or otherwise unsuitable soil exists near the ground surface and vertical loads must be carried to strong soils at depth. Deep foundations have a number of other uses, such as to resist scour; to sustain axial loading by side resistance in strata of granular soil or competent clay; to allow above-water construction when piles are driven through the legs of a template to support an offshore platform; to serve as breasting and mooring dolphins; to improve the stability of slopes; and for a number of other special purposes.

Several kinds of deep foundations are described in Chapter 5 and proposals are made regularly for other types, mostly related to unique methods of construction. The principal deep foundations are driven piles and drilled shafts.

Figure 1.3   Shallow foundations under construction.

The geotechnical design of these types of foundations under axial loading is presented in Chapters 10, 11, and 13, and the design under lateral loading is discussed in Chapters 12 and 14.

A group of piles supporting a pile cap or a mat is shown in Figure 1.4a. If the spacing between the piles is more than three or four diameters, the piles will behavior as individual piles under axial loading. For closer spacing, the concept of *pile–soil–pile interaction* must be considered. The analysis of pile groups is presented in Chapter 15. A particular problem occurs if a pile is embedded deeply in a concrete mat, as shown in Figure 1.4b. The difference in the behavior of a pile with a head free to rotate and a pile with a head fixed against rotation is dramatic. The real case for an embedded pile is that it is neither fixed nor free, but the pile-head restraint can be described with a linear or nonlinear relationship between pile-head rotation and moment.

The driving of a pile to support an offshore platform is shown in Figure 1.5. A template or jacket is set on the ocean floor with its top slightly above the water surface. The piles are driven and welded to the jacket; the deck can then be placed. In the figure, the pile is driven with a steam hammer that swings freely. The pile is marked along its length so that the engineer can prepare a driving record (number of blows required to drive the pile a given distance).
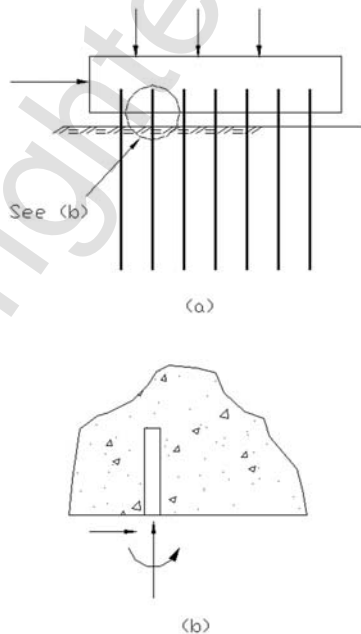

Figure 1.4 (a) Group of piles supporting a pile cap. (b) Loading of top of pile embedded in concrete for solving for the moment–rotation relationship.

Figure 1.5 Vertical pile being driven at offshore site with a swinging steam hammer.

1.2.3   Hybrid Foundations

A complex problem occurs if the mat shown in Figure 1.4a rests on the ground surface rather than with space below the mat. A solution of the problem has been presented by Zeevaert (1972) in a discussion of "compensated" foundations. The problem has received attention recently (Franke et al., 1994; Poulos, 1994; Viggiani, 2000; Cunha et al., 2001). As noted earlier, the zone of significant stresses beneath a mat will be relatively large, leading to a relatively large settlement before the working load on the mat is attained. The piles are usually friction piles, where the load is carried in side resistance, and the foundation is termed a *piled raft.*

In some cases, the piles are placed in a regular pattern; in other cases, the placement is strategic in order to lessen the differential settlement of the mat. The analysis must consider the vertical loading of the soil from the mat that affects the state of stress around the piles. Further analysis of the behavior of the mat must consider the presence of the piles that serves to reinforce the soil beneath the mat. Therefore, the modeling of the problem of the piled raft for an analytical study is done by finite elements.

The observation of the performance of piled rafts where instrumentation was employed to measure the distribution of the axial loading and where the settlement of the structure was measured carefully (Yamashita et al., 1994, 1998) provides the opportunity for a case study to validate the analytical technique. Additional data on the performance of piled rafts have been presented by Franke et al. (1994).

1.3   CONCEPTS IN DESIGN

1.3.1   Visit the Site

The value of a visit to the proposed site for the construction of a foundation from the point of view of geology is discussed in Chapter 2. Not only can information be gained about the geology of the area, but other features of the site can also be considered. The topography, evidence of erosion, possible response of the foundations of existing structures, and accessibility of construction equipment are items of interest.

The engineer will wish to consult with local building authorities to get information on criteria with regard to requirements for new construction. The locations of underground utilities should be obtained from the relevant agencies prior to the visit, and the presence of overhead lines should be observed.

1.3.2   Obtain Information on Geology at Site

Except for the very small job where foundation design is straightforward, the engineer will want to employ the appropriate *standard of care* by obtaining available information on the geology at the proposed construction site. Chap-

ter 2 lists a number of governmental agencies that provide information on the local geology. The engineer will wish to obtain such information, which could have an impact on how the subsurface information is subsequently developed.

1.3.3 Obtain Information on Magnitude and Nature of Loads on Foundation

Obtaining information on the magnitude of the loads to be sustained by a structure would seem to be simple, but such is not the case. In many instances, when foundations are being designed, the structural design is continuing. Furthermore, a substantial difference exists between the factor of safety being employed by the structural engineer and by the foundation engineer. The foundation engineer wishes to know the *working* load to be sustained by the structure, which means the unfactored dead load and live load. Then the working load is factored upward to design the foundation, with the selected factor accounting principally for the uncertainties associated with the soil properties and the analytical procedure being employed.

In many instances, statistics play an important role in determining loads on a structure. Offshore structures are designed to resist the largest storm that may occur once in perhaps 100 years. Offshore and onshore structures may be designed to resist the maximum earthquake that could occur in the location of the proposed structure.

If uncertainties exist in determining the magnitude of the loading, detailed discussions are in order among the various engineers, probably including representatives of the owner of the structure. A detailed discussion of the safety factor, including formal recommendations by agencies that employ load-and-resistance-factor design (LRFD), is strongly advised.

Two principal problems for the foundation engineer are the adequacy of the analytical technique to be employed and the adequacy of the properties of the soil to reflect the behavior of the soil in supporting the structure. The reader will gain insight into the adequacy of the analytical procedures in studying the various chapters. With respect to soil properties, Chapters 3 and 4 will be useful. In summary, the foundation engineer frequently wishes to know as precisely as possible the load to be sustained by the foundation and, at some stage in the work, wants to employ a global factor of safety to account for uncertainties in theory and soil properties.

1.3.4 Obtain Information on Properties of Soil at Site

A number of techniques may be employed to perform a subsurface investigation, as presented in Chapter 4. If possible, a staged investigation should be employed, with the first stage aimed at identification and classification of the soils at the site. The selection of the foundation, whether shallow or deep, could be based on the results of the first-stage investigation. The second stage

would focus on determining the necessary properties for the design. The work in the second stage could be minor or extensive, depending on the nature of the design and the soils at the site.

A conceptual curve can be plotted to show how the total cost of a structure can be influenced by the cost of the investigation of the soils. At some stage, the maximum amount of information could be gained to minimize the cost of the structure. Most subsurface investigations do not allow for the optimum approach due to either time or cost constraints. The knowledgeable foundation engineer will benefit the owner and all other professionals on the job by presenting lucid and convincing arguments for a subsurface investigation that is fully adequate.

1.3.5   Consider of Long-Term Effects

The foundation engineer is obligated to consider effects on the structure that could occur with time. Examples are settlement due to consolidation of clays, settlement due to compaction of sand by vibration, movement of a foundation due to swelling and shrinkage of a clay, and the adverse effects of time-related erosion.

1.3.6   Pay Attention to Analysis

The methods of analysis presented in this book contain many equations that include parameters dependent on soil properties. The available computer programs are so efficient that parametric studies can be undertaken and completed in a short time. The engineer is obligated to study the methods proposed to gain a full understanding of the purpose and appropriateness of the procedure. Full advantage should be taken of the speed of modern computers.

A simple study that is always worthwhile is to use the results of the subsurface investigation and to select lower-bound and upper-bound values of the relevant parameters. Analyses can be made with the two sets of data to allow the selection of properties to be used in the final design.

1.3.7   Provide Recommendations for Tests of Deep Foundations

Studies of the design of foundations at a particular site may indicate the need to perform a full-scale load test of the deep foundation to be employed in the construction. A justification for the test would be that no data are available on the performance of the type of foundation to be used in the soil that exists at the site. A further justification exists if the engineer can show that the cost of the deep foundations to be used without the test would be reduced by more than the cost of the test if testing is approved.

1.3.8 Observe the Behavior of the Foundation of a Completed Structure

Some very successful foundation engineers have made extensive use of formal observation. This will allow corrections to be made if the observation shows deficiencies.

Even if formal observation is not employed, many engineers make an effort, with the consent of the owner, to observe the performance of the foundation with time. On some occasions, instruments may be used to gain information on the distribution of loading to the various elements of the foundation. Such information is extremely valuable.

PROBLEMS

P1.1. Obtain a current copy of a magazine on engineering projects and write a brief exposition of the nature of one such structure, the general nature of the soil conditions, and the kind of foundation being employed for the project. If possible, list the reasons the engineer chose the particular type of foundation.

P1.2. In preparation for considering the behavior of a pile under lateral loading with respect to the pile-head restraint, (a) compute the deflection of a cantilever beam with a load at the free end and then (b) one with the end fixed against rotation but free to deflect.

P1.3. Visit a construction site in your area. Take a photograph of the foundation if allowed and describe it as well as possible.